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Seismic Vulnerability Assessment of Masonry Buildings in Seismic Prone Regions: The Case of Annaba City, Algeria

Allaeddine Athmani, Abdelhacine Gouasmia, Tiago Ferreira, Romeu Vicente

***Abstract*—**Seismic vulnerability assessment of masonry buildings is a fundamental issue even for moderate to low seismic hazard regions. This fact is even more important when dealing with old structures such as those located in Annaba city (Algeria), which the majority of dates back to the French colonial era from 1830. This category of buildings is in high risk due to their highly degradation state, heterogeneous materials and intrusive modifications to structural and non-structural elements. Furthermore, they are usually shelter a dense population, which is exposed to such risk. In order to undertake a suitable seismic risk mitigation strategies and reinforcement process for such structures, it is essential to estimate their seismic resistance capacity at a large scale. In this sense, two seismic vulnerability index methods and damage estimation have been adapted and applied to a pilot-scale building area located in the moderate seismic hazard region of Annaba city: The first one based on the EMS-98 building typologies, and the second one derived from the Italian GNDT approach. To perform this task, the authors took the advantage of an existing data survey previously performed for other purposes. The results obtained from the application of the two methods were integrated and compared using a geographic information system tool (GIS), with the ultimate goal of supporting the city council of Annaba for the implementation of risk mitigation and emergency planning strategies.

***Keywords*—**Annaba city, EMS98 concept, GNDT method, old city center, seismic vulnerability index, unreinforced masonry buildings.

I. Introduction

THE exponential increase of big cities all over the world have been accompanied by the inadequate occupancy of the soil together and the growth of the industrial and economic activities in and around them.

It is generally recognized that high concentration of population, infrastructures and valuables exposed assets, make these areas highly vulnerable to seismic risk, especially, the old city zones. Consequently, major losses are expected even for moderate intensity earthquakes.

A. The Old Town of Annaba City

Annaba city had a population of over 260.199 people according to the 2011 census [1]. The historical buildings dominate the building stock and constitute a priceless and irreplaceable urban heritage part of the city, where the majority of them were constructed during the colonial French era between 1830 and 1964.

The old historical center of Annaba city, usually called as "Place d'arme", is known by its dense residential and commercial districts with narrow alleys and streets (Fig. 1). Generally, the buildings typologies are in rubble stone, adobe or brick masonry with timber, composite steel/masonry or reinforced concrete.

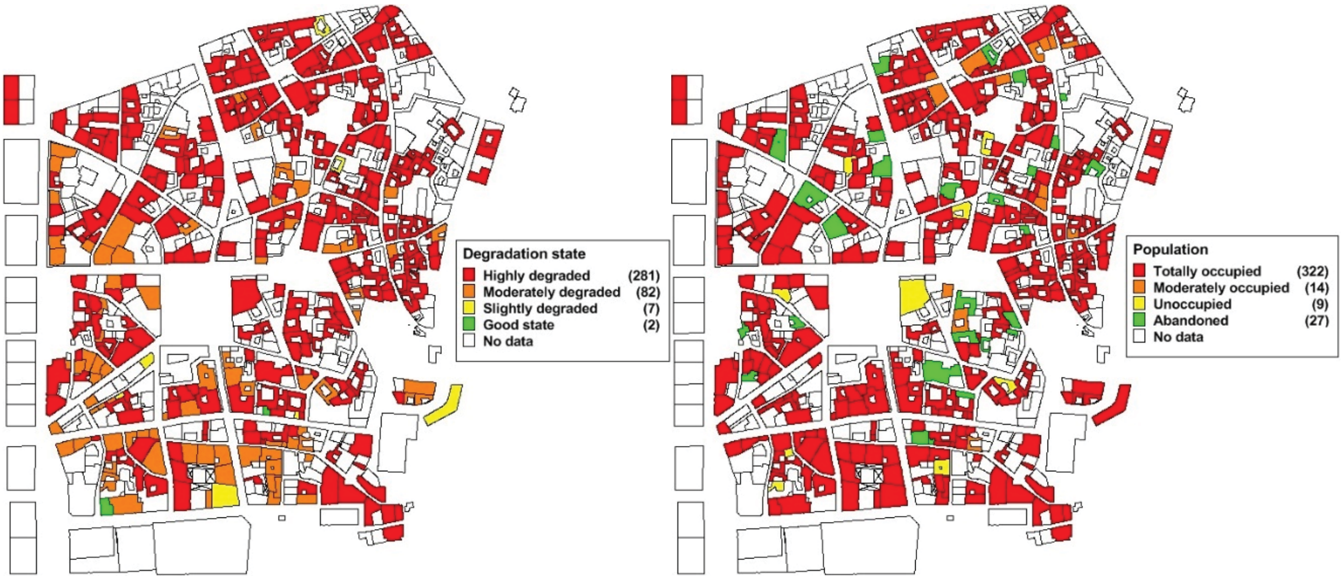
The building stock is in very poor condition and show an undesirable deterioration level in the interior and the exterior of the constructions (Fig. 2 (a)), which shelter a dense population shown in Fig. 2 (b). In this regard, it is worth to be mentioned that these buildings present high levels of vulnerability and consequently, a significant damage can be expected in the case of a seismic event, even moderate. Therefore, a seismic risk assessment of the region is necessary.

Fig. 1 Aerial view of the old area of Annaba city (Algeria)

A. Athmani is PhD student with the University of Badji Mokhtar, Annaba, Algeria (corresponding author to provide phone: +213792346685; e-mail: allaeddine.athmani@gmail.com).

A. Gouasmia, Assistant Professor is with the University of Badji Mokhtar, Annaba, Algeria, (e-mail: abdelhacine.gouasmia@univ-annaba.dz).

T. Ferreira, Researcher, and R. Vicente, Assistant Professor, are with the University of Aveiro, Aveiro, Portugal, (e-mail: tmferreira@ua.pt, romvic@ua.pt).



(a) (b)

Fig. 2 Masonry building in the study area: (a) degradation state; and (b) occupation

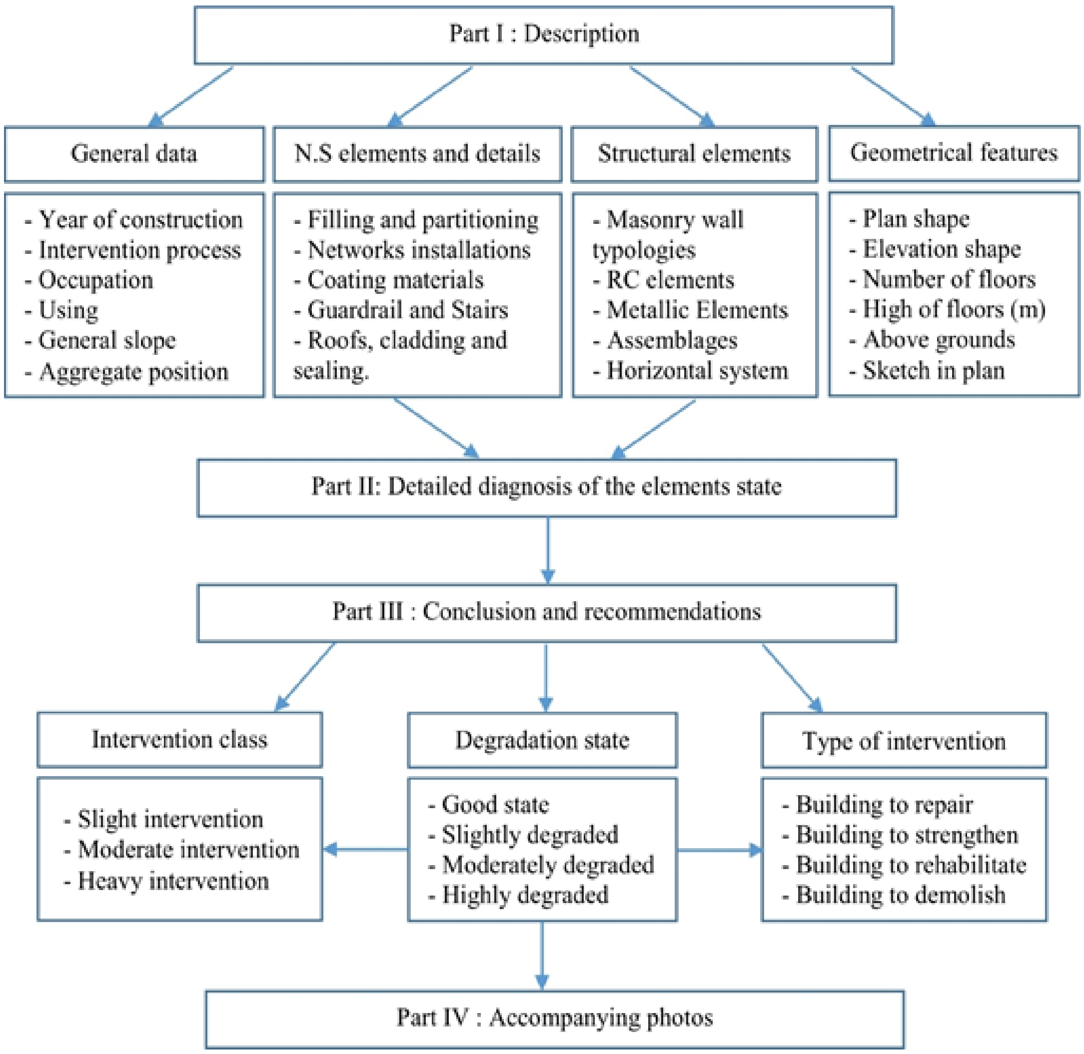


Fig. 3 The different parameters that compose the CTC data sheets

B. Inspection and Appraisal - Database

The state of deterioration of the historic masonry buildings located in the old town of Annaba city, threatens the life of thousands inhabitant. Due to frequent complaints and some tragic events occurred in this area, namely the death of a whole family and inhabitants due to collapse of old buildings and façade walls, the Direction of Urban Construction and Habitat (DUCH) has launched, in collaboration with the technical organism officially in charge of the Technical Control of Construction of Annaba city (CTC), a program to carry out a building-by-building complete identification and inspection survey for the aim of renovation and rehabilitation of all the historical masonry buildings [2].

Taking advantage of the vast set of data obtained from the surveys, the authors assessed the seismic vulnerability of 372 buildings over a total of 602 (see Fig. 5). The main ingredients of CTC's datasheets are schematically presented in Fig. 3 to give an overview of the type of items surveyed.

The synthesis of CTC data was used to classify buildings in one of the four classes of degradation (good state, slightly degraded, moderately degraded and highly degraded) to propose the types of interventions to be undertaken (repairs, strengthen, etc.) according to their degree of classification (slight, moderate and heavy) (Fig. 3).

II. Vulnerability Analysis

According to reference [3], the seismic vulnerability is the internal risk factor of the considered exposed elements such as a building, or at a larger level, an urban area with a building stock of similar characteristics to seismic hazard [4].

In order to perform an accurate seismic vulnerability analysis of historical masonry buildings based on the vulnerability index methods, the maximum available information related to buildings strength that increase or reduce its seismic behavior must be considered, either from its own characteristics, or even from the aggregate environment they belong to.

III. Vulnerability Assessment Methods

In the last few years, different methodologies for seismic assessment and classification of existing buildings were developed [5]. The analysis of literature review highlights the importance of the methodologies based on seismic vulnerability index at large-scale, which are considered to be a good tool to estimate the seismic construction's quality. Among these methods, the authors have put emphasis on two approaches that are close in their original concept, the first one based on the EMS-98 building typologies [6], and the second one derived from the Italian GNDT approach [7].

A. EMS 98 Concept

Based on the buildings classification typologies and the five non null damage states of the European Macroseismic Scale EMS-98, labeled as Slight, Moderate, Substantial to Heavy, Very Heavy and Destruction [6], a methodology called "macro-seismic method", was developed in its version in the framework of the European project Risk-UE [8].

The RISK-UE method defines the seismic action as a macro-seismic intensity and the building vulnerability by mean of a typological index IV* (see Table I) which is defined as the most probable value of the final vulnerability index [9]. This index is then modulated in terms of the specific structural criteria of each structure ΔV_m, such as the number of floors, the conservation state, horizontal and elevation irregularity. Therefore, the difference in height between adjacent buildings is taken into account, as well as their position in the aggregate block [10].

Furthermore, two items are added taken into account the deterioration state of the important elements of the resisting system and the horizontal system. Based on the detailed data survey, four classes of deterioration state were considered, namely: slight, moderate, heavy and very heavy. Two ranges of modifier values, 0.02 to 0.08 and 0 to 0.06, were in addition defined for the two above stated elements, respectively. The sum of all the modifier parameters will be added to the basic index IV^* to work out the final index V that is normalized between 0 for high seismic resistance buildings, and 1 for most vulnerable buildings.

$$V = I_v^* + \sum \Delta V_m \tag{1}$$

From this index, it is then possible to define, the mean damage grade expressed by [11]:

$$\mu_D = 2.5\left[1 + tanh\left(\frac{I+6.25-13.1}{2.3}\right)\right] \tag{2}$$

The value of μ_D varies between 0 (no damage) and 5 (severe damage or destruction), being defined according to the EMS98 scale.

From the μ_D value, the distribution of damages and the percentage of building situated in a certain damage level can be determined by applying a beta distribution [12].

According to the existing database, and based on the RISK-UE typologies, it was thus possible to evaluate and map the distribution of buildings in the urban district under study (Table I).

TABLE I
DISTRIBUTION OF BUILDING TYPOLOGIES ACCORDING TO RISK-UE METHOD

Typologies Masonry	IV*	Description	∑	%
M1.1	0.873	Rubble stone	86	23.12
M1.2	0.74	U. Masonry (old bricks)	29	7.80
M1.3	0.616	Massive stone	1	0.27
M2	0.84	Adobe	61	16.40
M3.1	0.74	Wooden slabs	39	10.48
M3.2	0.776	Masonry vaults	40	10.75
M3.3	0.704	Composite steel and masonry slabs	100	26.88
M3.4	0.616	Reinforced concrete slabs	16	4.30
		Total	372	100

B. GNDT Concept

The second methodology adapted herein comes as an adaptation of the original GNDT II approach for the masonry buildings of Annaba city, which is improved and simplified by: (i) giving a fixed vulnerability class of certain parameters for all types of construction defined on the basis of the general characteristics of the built environment; (ii) clarifying the definition of some of the most important parameters [13], [14], [15] and modulated according to the available data [16]; (iii) introducing new parameters that take into account the overlooked building features of the built environment of Annaba city. This method uses the weighed sum of 14 parameters in the formulation of the seismic vulnerability index. Likewise the GNDT II level approach, these parameters were distributed into 4 vulnerability classes of growing vulnerability classes: A, B, C and D. Subsequently, a weight p_i was assigned to each parameter, ranging from 0.25 for the less important parameters (in terms of structural vulnerability) to 2.5 for the most important (see Table I). The vulnerability index in the present methodology ranges between 0 and 540. Therefore, the vulnerability index is given by:

$$I_v^* = \sum_{i=1}^{14} C_{vi} \times P_i \tag{3}$$

Then, for easy use, the value obtained by the weighted sum can be normalized within the range, $0 \leq I_v \leq 100$.

Parameter P2 (Organization of resisting system) was estimated as a fix vulnerability class for all constructions according to the general organization and features of the pilot-scale building area under study, because its corresponding information are partially known from the existing data survey. In the same way, a fixed vulnerability class was proposed to the mechanical parameter P3 (Conventional seismic strength), because such parameter requires detailed information from the structural plans and material features that are not available in the CTC data. In a broad sense, without going into great detail for all of them, the addition of the parameters P1, P5, P7 and P12 provides: the typology of the resisting system according to EMS-98 scale (P1); the height of the building (P5); the interaction between contiguous buildings (P7), a very important feature when assessing buildings in urban areas; and the interventions process (P12), it holds the reinforced processes or the anomalies at constructions level which we observe in our society (the additions or the suppressions of certain elements) that affects the capacity of buildings [17]. Finally, [9] subsequently proposed an expression of the associated expected average damage as a function of the expected macroseismic intensity I_{EMS-98} (EMS-98 scale) and of the vulnerability index I_v (3).

$$D = 0.5 + 0.45\, aractan\big(0.55(I_{EMS-98} - 10.2 + 0.05 I_v)\big) \tag{4}$$

The damages assessed on a scale from 0 to 1 may be transcribed on the EMS-98 scale by applying the equivalence described in Fig. 4.

IV. Application of the Two Vulnerability Index Method to the Masonry Building of the Old Town of Annaba City

The masonry building stock of the old center of Annaba city was assessed, quantifying for each building the vulnerability index, V (1) and I_v (Table II) according to the two modified methods RISK-UE and GNDT level II respectively (see Fig. 5).

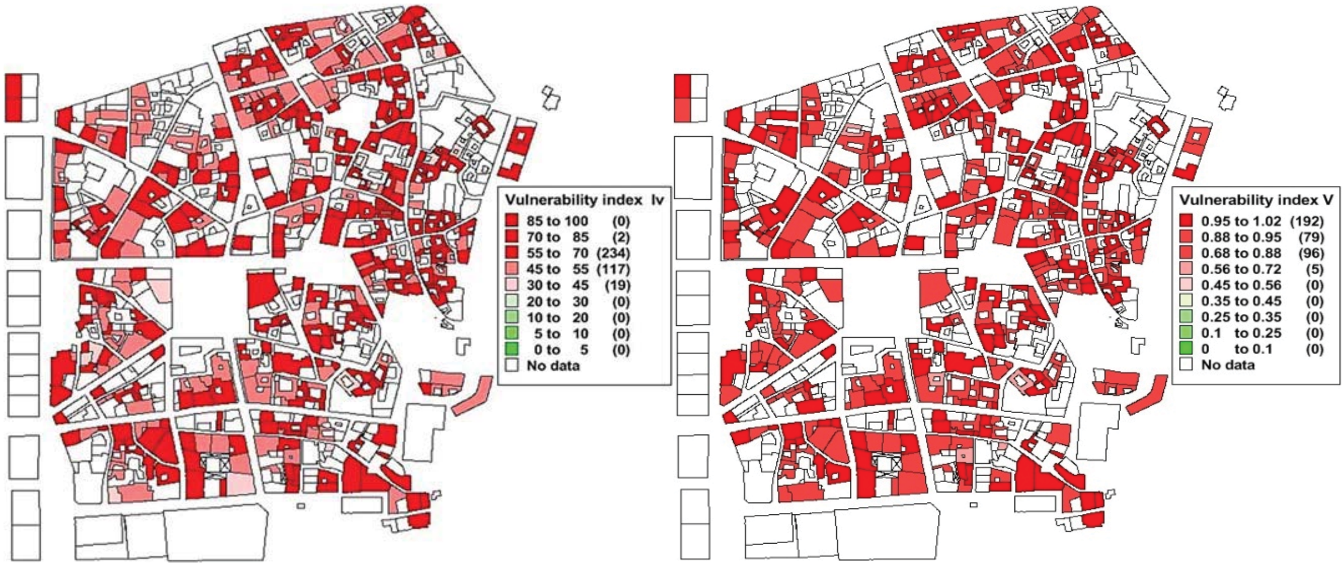
TABLE II
PARAMETERS AND VULNERABILITY INDEX (I_v)

Parameters		Vulnerability class Cvi				Weight	Vulnerability Index
		A	B	C	D	Pi	
P1	Typology of resisting system	0	5	25	45	2.50	$I_v^* = \sum_{i=1}^{14} C_{vi} \times P_i$
P2	Organization of resisting system	0	5	25	45	0.75	
P3	Conventional strength	0	5	25	45	1.50	
P4	Maximum distance between walls	0	5	25	45	0.25	
P5	Number of floors	0	5	25	45	0.75	
P6	Location and soil conditions	0	5	25	45	0.75	$0 \leq I^*v \leq 540$
P7	Aggregate position and interaction	0	5	25	45	0.75	
P8	Plan configuration	0	5	25	45	0.50	
P9	Regularity in height	0	5	25	45	0.50	
P10	Horizontal diaphragms	0	5	25	45	1.00	
P11	Roof system	0	5	25	45	1.00	
P12	Intervention process	0	5	25	45	0.50	
P13	Fragilities and conservation state	0	5	25	45	1.00	Normalized index 0≤IV≤100
P14	Non-structural elements	0	5	25	45	0.25	

Fig. 5 shows that according to the RISK-UE method 97% of the assessed buildings have a vulnerability index V value over 0.72 (equivalent to vulnerability class "A" in the EMS-98 scale [6] where maximum and minimum values obtained from the detailed assessment are 0.60 and 1.02, respectively. In what regards to the GNDT concept, almost the same amount (94%) of the assessed buildings fall into the vulnerability class "A" with an I_v value over 45, where maximum and minimum I_v values obtained from the detailed assessment are 76.62 and 30.09, respectively.

EMS98 scale	1	2	3	4	5
Masonry					
Average damage D	[0.0 – 0.2[	[0.2 – 0.4[	[0.4 – 0.6[	[0.6 – 0.8[	[0.8 – 1.0[

Fig. 4 Equivalence between the level of damage indicated in EMS98 and the numerical values of the average damage D (0 < D < 1) computed in GNDT [18]



(a) (b)

Fig. 5 Vulnerability distribution: (a) I_v according to the modified GNDT level II; and (b) V according to the modified RISK-UE

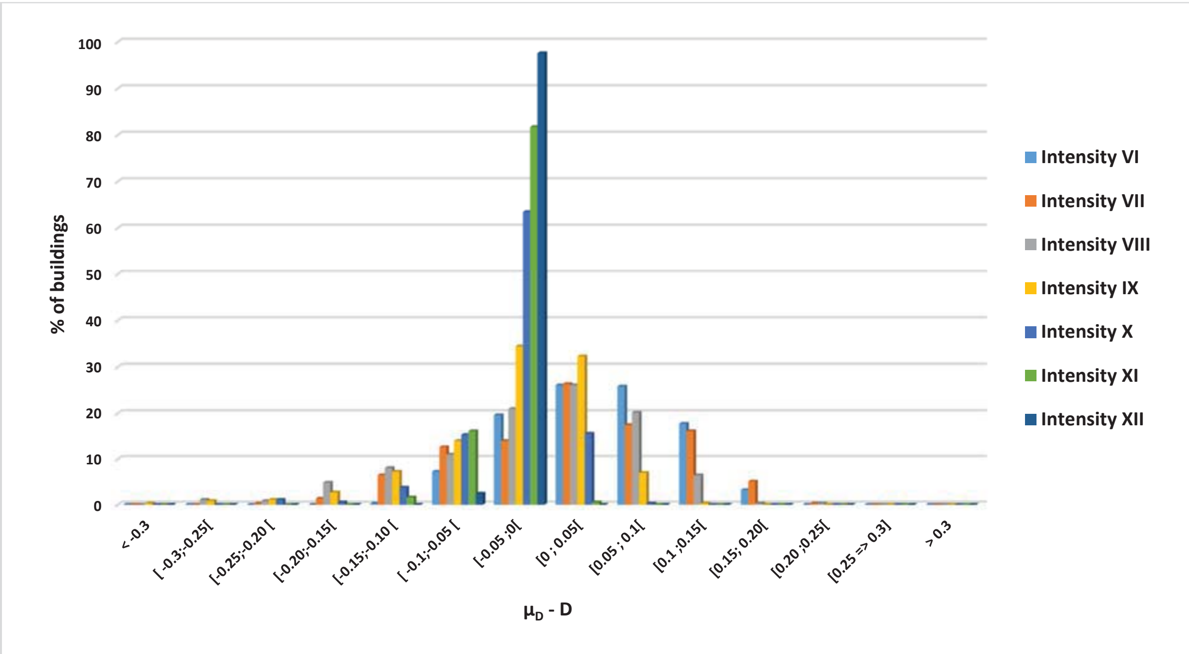


Fig. 6 Percentage of residual ($D_R = \mu_D/5 - D$) of damage computed in two modified methods (Risk-UE and GNDT) for different EMS98 intensities

V. Damage Estimation and Scenarios

Although Annaba city is classified as a moderate seismic hazard area according to Algerian code with a maximum intensity of VI degrees on the MSK intensity scale [19], the expected damage is estimated for all intensities (Fig. 6) using the mean damage grades, μ_D, (2), and D, (4). The reliability of the results obtained was analyzed through the residual value D_R, between the Risk-UE (slightly modified) method and the modified GNDT II method (see Fig. 6), computed as follows: $D_R = \mu D - D$ [20]. As can be seen in that figure, the residual value for almost the totality of individual buildings ranges between -0.2 and 0.2, corresponding to less than one degree on the EMS98 damage scale (Fig. 4). Additionally, the results included in Table III show that the residual value is almost linear for all intensities: For an intensity VI, 100% of masonry buildings have a residual value lower than 0.2, 99% for the intensity VII, 98%, 98% and 99% for the intensities VIII, IX and X respectively, which proves that the masonry buildings were well surveyed and are sufficiently detailed in the CTC database.

Although the CTC data did not allow direct estimation of parameters P2 and P3, as defined in the GNDT method, we consider it as a very valuable database. Moreover, the proposed modifications implemented on the two methodologies (RISK-UE LM1 and GNDT level II) gives reliable estimates of the seismic vulnerability of buildings and therefore these methods can be used as a first step to assess the seismic-prone regions at a larger scale. For the analysis of masonry buildings located in the old town of Annaba city, histograms of the distribution of the mean damage values (expressed in EMS-98 grades) show that the two methods give similar results. Furthermore, convergence between the two methods is presented in the damage distribution histogram (Fig. 7) as another common point of the repartition of the major portion of the study area in two damage grades for all intensities which explains the real risk and high vulnerability of the assessed buildings.

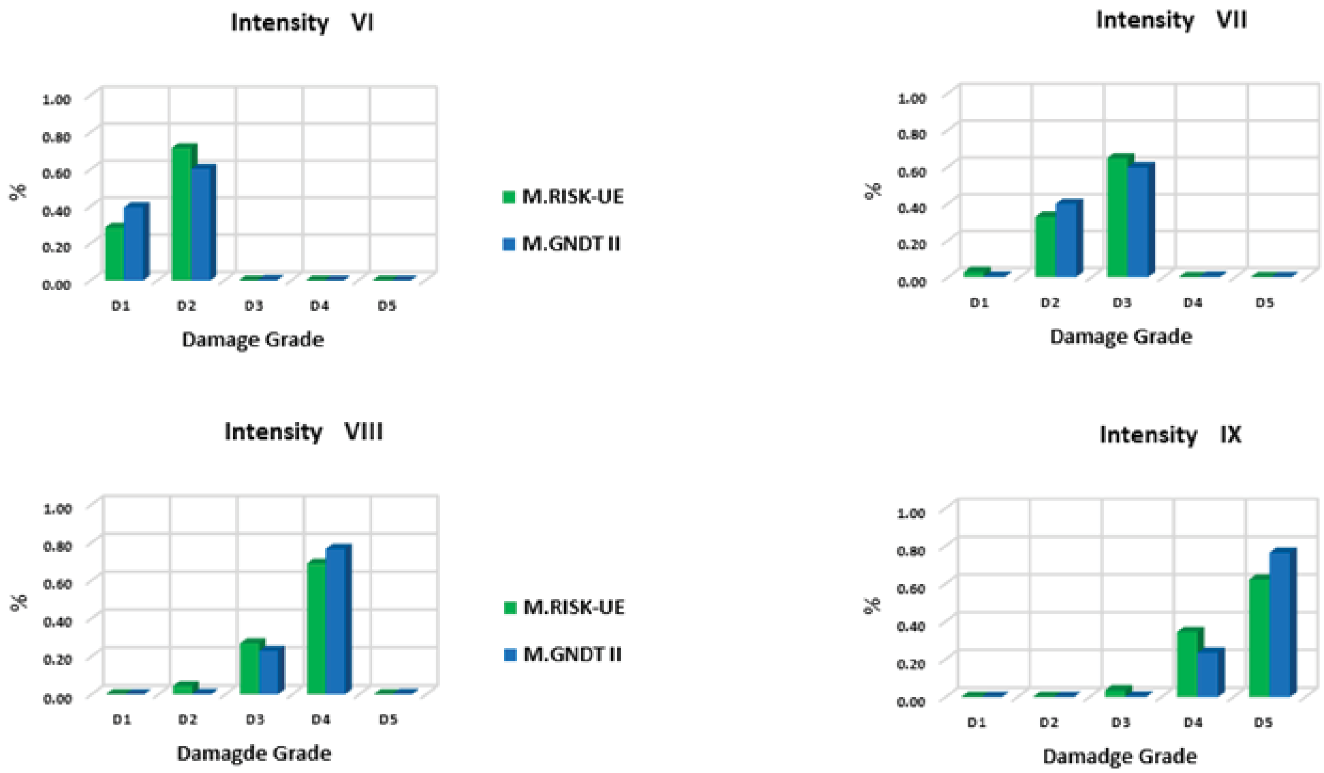


Fig. 7 Distribution of damage grades according to EMS degrees

TABLE III
PERCENTAGE OF RESIDUAL ($D_R=\mu_D/5$-D) FOR DIFFERENT EMS-98 INTENSITIES

Intensity	VI	VII	VIII	IX	X
[-0.1; 0.1]	80	71	78	88	95
[-0.15; 0.15]	97	93	92	95	98
[-0.2; 0.2]	100	99	98	98	99
[-0.25; 0.25]	100	100	99	99	100
[-0.3; 0.3]	100	100	100	100	100

VI. DISCUSSION AND CONCLUSIONS

The present paper summarizes a seismic damage estimation study carried out from an "incomplete" non-dedicated building inventory through which two different existing methods, modified according to the specificity of the built-up area under study, were applied. The implicitly introduction (for the GNDT level II method) and the explicitly involving (for the RISK-UE method) of the degradation state give very representative outcomes which correlated well the features and the general fragilities of surveyed buildings, proofing the reliability of the seismic vulnerability assessment methodologies used. In addition, and even though the Annaba city is located in a moderate-to-low seismic hazard region, the results obtained show the absolute level of seismic risk for the old masonry buildings to any eventual moderate seismic event. The level of damage estimated for these buildings (using the two modified methods) is an indicator of its low resistance against seismic actions and the moderate to high values of damage and loss obtained for different intensities are consequence of the high vulnerability of these buildings. In this context, the results obtained show that the expected mean damage is very important for intensities VIII and IX, with an average damage grade around 3–4 for intensity VIII and 4-5 (near collapse) for intensity IX. Catastrophic events are expected for intensity X with total collapse of all the constructions under study.

From a methodological point of view, the comparison of the results of the two methods has revealed two interesting facts:

1) The vulnerability assessment of existing buildings using the selected macro-seismic methods (RISK-UE and GNDT level II) based on a non-dedicated building data set are suitable for application at an urban scale and exhibit a very satisfactory agreement for masonry built heritage in

seismic prone regions;

2) Although preliminary, this study gives solid grounds to stress a rigorous implementation of appropriated retrofitting of the old masonry buildings to reduce their seismic physical damage. Moreover, mitigation policies should be established in order to preserve human lives and properties, even in moderate to low seismic hazard regions such as Annaba city.

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